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# **Effect of mix design methods on the mechanical properties of steel fibre-reinforced concrete prepared with recycled aggregates from precast waste**

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## **Abstract**

This research investigates the impact of mix design methods on the mechanical characteristics of steel fibre-reinforced concrete (SFRC) made with recycled aggregates (RA) obtained from a precast waste concrete. The experimental campaign was carried out in two phases. In phase I, three types of steel fibre (SF) differing only in shape were examined. Then, eight mixes were formulated, considering a range of SF volume ratios from 0.125% to 1.5%, using both normal and the Equivalent Mortar Volume (EMV) mix design methods. In phase II, a reference mix and two recycled aggregate concrete mixes were developed, one designed with normal method and the other with the EMV technique and incorporating their associated optimum SF content obtained in phase I. The results show that the mechanical properties of SFRC proportioned with the EMV approach is not adversely affected and that water absorption capacity of the concrete is improved with this method compared to the traditional method. Also, mix design method adopted for recycled concrete affects the optimum SF volume ratio.

**Keywords:** Recycled aggregate concrete, steel fibre, optimization, mix design, precast waste.

## HIGHLIGHTS:

- The use of different mix design methods attracts different optimum steel fibre content.
- Equivalent Mortar Volume (EMV) mix proportioning technique can be applied to steel fibre-reinforced recycled concrete.
- The EMV mix design method is more cost-effective than its conventional counterpart.
- The EMV guide requires over 68% more superplasticizer compared to the traditional method.
- The presence of SF increases pore density thereby affecting the durability of the concrete.

**Abbreviations:** Attached mortar volume (AMV); Blended aggregate concrete (BAC); Construction and demolition waste (CDW); Equivalent mortar volume (EMV); High performance concrete (HPC); Natural aggregate (NA); Natural aggregate concrete (NAC); Natural concrete (NC); Natural coarse aggregate (NCA); Natural fine aggregate (NFA); Natural virgin aggregate (NVA); Recycled aggregate (RA); Recycled aggregate concrete (RAC); Recycled coarse aggregate (RCA); Recycled fine aggregate (RFA); Steel fibre (SF); Steel fibre-reinforced concrete (SFRC); Steel fibre-reinforced blended aggregate concrete (SFRBAC); Steel fibre-reinforced recycled aggregate concrete (SFRRAC)

## 1. Introduction

Recycling of concrete waste remains an important step in the pursuit of global environmental sustainability [1]. This is because, the use of recycled aggregates (RA) not only saves the diminishing natural resources but also offers a relief to the pressure imposed on landfills [2]. By RA here is meant the combination of recycled fine aggregate (RFA) and recycled coarse aggregate (RCA), hence, except where otherwise stated in this work, RA implies the union of RFA and RCA. Similarly, natural aggregate (NA) is regarded here as a combination of natural fine aggregate (NFA) and natural coarse aggregate (NCA). This emphasis is necessary as these acronyms have been used interchangeably in some literature without clear definitions, thereby

misleading some interpretation of results. However, most studies in the past concentrated more on the replacement of coarse aggregate with RCA [3–8], thus undermining the possibility of incorporating RFA for the production of concrete suitable for structural applications. According to Pedro et al. [9], there is a serious restriction or even ban in the use of RFA for concrete manufacture. The reason is not farfetched from that the finer material has a higher amount of mortar than its RCA counterpart [10], resulting in aggregates of high absorption capacity and a concrete of reduced workability [11]. Nevertheless, the use of 20% RFA has no detrimental effects on workability [12]. A few accounts of some studies that utilized RCA as well as RFA is presented here.

Pedro et al. [9] used RA obtained from a precast waste, of mean compressive strength of 74.5MPa (at unknown age but more than 28 days old) to investigate the influence of RA (incorporated at various percentages, up to 100%) on recycled aggregate concrete (RAC) properties. They showed that compressive and tensile strengths of the RAC are 16% and 38.2% lower, respectively, compared to those of the reference concrete made of NA. Their finding agrees with that of Khoshkenari et al. [2] who reported up to 32% decrease in the tensile strength of RAC prepared with 100% replacement of NA. Both studies recorded a higher reduction in the tensile strength of RAC than in the compressive strength. On the other hand, Khatib [13] noted a further cementing action after 28 days of curing, which resulted in a higher rate of strength development for the concrete made with RFA, relative to that of the control with NA. Corinaldesi and Moriconi [14] who investigated the influence of mineral additives on the properties of 100% RAC, upheld that concrete of satisfactory characteristics can be attained with RA, using a suitable mix proportioning method.

Ajdukiewicz and Kliszczewicz [15] designed a high performance concrete (HPC) using RA derived from demolished concrete of moderate to high strength (35 – 70MPa), of which the authors knew the history of all the six structures involved. They concluded that RA sourced

from quality concrete is useful for making HPC, however, they advised against the use of RFA for certain reasons not mentioned. Another study by Tu et al. [16] showed that RA could be applied to HPC purposes, provided that the physical properties of RA satisfy the recommendations for HPC. Liu and Chen [17] also reported a shortfall in both compressive and tensile strengths at all ages of high strength concrete developed using RA.

Furthermore, the addition of steel fibre (SF) in RAC mixes has recently been investigated for normal, self-compacting and high performance concretes [18–24]. Only one out of these studies included RFA, and literature on the combined effect of SF and RFA in concrete is still scarce. But the quantity of RFA produced during the crushing process of concrete rubble is about twice that of the RCA and the idea of partial replacement of NA restricts the full-scale integration of concrete waste in concrete production [17,25]. Therefore, there is a need to further investigate steel fibre-reinforced concrete (SFRC) prepared with both RCA and RFA.

The mix design methods most appropriate to RCA re-use has been debated at length and consequently, the focus of this research is to examine the effects of two such methods on the mechanical and durability properties of RAC incorporating SF. To this end, three types of SF which differ only in shapes (straight, hooked-ended and undulated) as well as the SF volume fractions appropriate to each mix design methods, were investigated. Compressive strength, splitting tensile strength, flexural strength and water absorption capacity are the properties of hardened concrete studied here. Also, all the important aggregates characteristics required for the design of the mixes were duly obtained using the relevant codes of practice.

## **2. Background**

Generally, RA is sourced from construction and demolition waste (CDW), returned ready-mix or precast waste [26–28]. From a combination of views, RA can be defined as a mixed materials of wood, reinforcements, bricks, concrete, soil, polymers, unbound stones, natural virgin

aggregate (NVA) with dry mortar held together by a weak bond [29–31]. This definition encompasses the various elements found in the sources of RA and, if all the elements but concrete and NVA are considered as impurities, then RA can be represented mathematically as:

$$RA = NVA + Dry\ mortar + Impurities \quad (1)$$

The level of impurity in equation (1) depends mainly on the source of the RA [32]. For instance, Thomas et al. [33] defined CDW as “waste generated in new construction, repair, remodelling, renovation and demolition.” Such a RA obtained from these activities would be more contaminated than those sourced from comparable precast waste (whose concrete is described as very good without contaminants [34] and of a considerable superior quality compared to RA from other sources [34,35]). Hence, for RA obtained from a precast waste, equation (1) can be reduced to:

$$RA = NVA + Dry\ mortar \quad (2)$$

However, irrespective of RA source, a number of factors have hampered its use in concrete making, especially for structural purposes. These include but are not limited to: (i) the variability in quality of RA [36–38], (ii) fragments of dry mortar attached to or present in RA [39,40], (iii) no universally accepted mix design method for RAC [37,41]. Nonetheless, finding a suitable mix design method for RAC mixes would help in tackling these challenges.

As a result, this study aims to determine the impact of mix design methods on the mechanical properties of RAC produced with SF and RA obtained from a precast reject. This is essential because the above Equation (2) suggests that RA from a precast waste is a hybrid material. Thus, the use of traditional mix design method meant for normal concrete consisting of NA, would result in a RAC of poor quality. Conversely, the properties of RAC designed by an alternative mix proportioning method developed by Fathifazl et al. [40] were improved relative

to those prepared by comparable normal method. This new mix design technique forms the basis for the present research in which both conventional and unconventional mix design methods are investigated experimentally. The conventional concrete is designed according to the American Concrete Institute (ACI) guidelines, while the unconventional concrete was prepared with the technique proposed by Fathifazl et al. [40] known as the “Equivalent mortar volume” (EMV) method. Although studies in the past have shown that the inclusion of SF in concrete enhances the mechanical properties of the concrete [19,20,22–24,42], no study to date (at least to the authors’ knowledge) has been carried out on SFRC using the EMV mix proportioning principles.

This research is important because, a change in mix design method, will affect the optimum SF content that gives the best performance. In essence, two optimization processes are conducted, one for each mix design method, to determine the amount of SF that best improves the characteristics of the RAC.

### **3. Experimental Program**

#### *3.1 Materials*

Apart from water and steel fibres, other materials used in this research were supplied by a precast concrete beam company. The RCA and RFA were obtained by crushing the precast waste in a Rubble Master Compact Crusher 70Go!™ and the resulting product was subsequently sieved. The NA used are also the original aggregates in the concrete rubble, and according to the company, every mix batch for production met a minimum cube strength of 40MPa after 24 hours. CEMEX CEM I 52.5R cement with the properties given in Table 1 and Sika ViscoCrete 335 superplasticizer conforming to BS EN 934-2 [43] were used for this study.

The fine aggregates (natural and recycled) for all concrete mixes were graded into three size fractions as follows: 0.075/0.57mm, 0.57/2.47mm and 2.47/4.75mm. On the other hand, the

coarse aggregates were graded into two size fractions viz: 4.75/10.00mm and 10.00/14.00mm.

The result of the characterization of the aggregates are presented in Table 2 and their particles size distributions are shown in Fig. 1 & 2.

The specific gravity of both fine and coarse RA is lower than those of their corresponding NA.

It should be noted that, whereas the oven-dry specific gravity of NFA increases with decrease in particles size, the reverse is the case for the RFA. Hence, the differences in the specific gravity of NFA and RFA, in the size order: 0.075/0.57mm, 0.57/2.47mm and 2.47/4.75mm are 32%, 24% and 13% respectively, in favour of NFA. The specific gravity of NCA is 12% higher compared to that of RCA, however, their values are independent of size fractions.

**Table 1.** Physical and chemical properties of cement.

Physical properties:												
Fineness (m <sup>2</sup> /kg)	Initial setting time (mins)	Expansion <sup>§</sup> (mm)		Loss on ignition (%)								
527	96	0.8		2.86								
Chemical composition by weight (%):												
SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	MgO	SO <sub>3</sub>	Na <sub>2</sub> O <sub>(eq)</sub>	Cl	FL	C <sub>3</sub> S	C <sub>2</sub> S	C <sub>3</sub> A	C <sub>4</sub> AF
19.99	4.75	2.91	63.77	1.13	3.56	0.65	0.05	2.02	47.84	26.3	8.33	9.67

Note: CEM I, 52.5R, <sup>§</sup>BS EN 196 – 1

**Table 2.** Properties of natural and recycled aggregates.

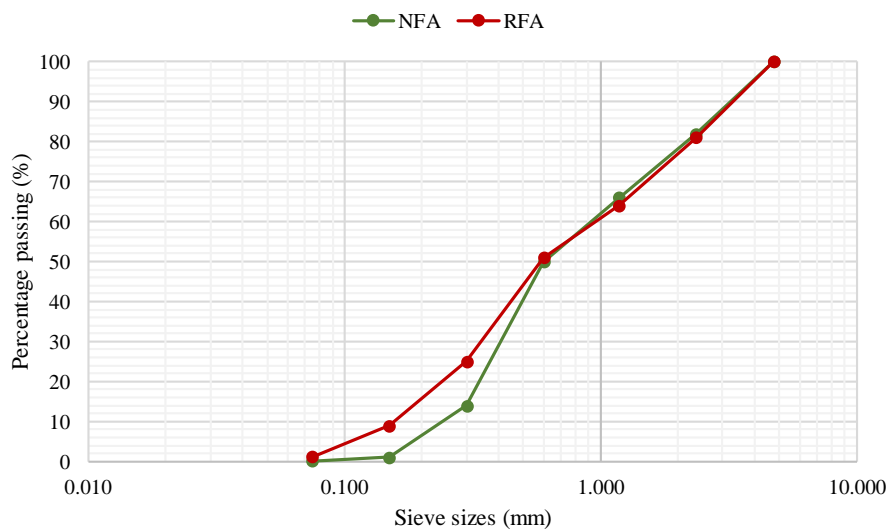
Property	NFA			RFA			NCA		RCA	
	Size fraction (mm)			Size fraction (mm)			Size fraction (mm)		Size fraction (mm)	
	0.075/ 0.57	0.57/ 2.47	2.47/ 4.75	0.075/ 0.57	0.57/ 2.47	2.47/ 4.75	4.75/ 10.00	10.00/ 14.00	4.75/ 10.00	10.00/ 14.00
Specific gravity:										
<i>Oven-dry</i>	2.62	2.57	2.48	1.78	1.96	2.15	2.60	2.62	2.30	2.30
<i>SSD</i>	2.63	2.60	2.52	2.10	2.20	2.34	2.63	2.64	2.42	2.42
<i>Apparent</i>	2.66	2.65	2.57	2.62	2.57	2.66	2.67	2.66	2.62	2.61
Water absorption (%)	0.6	1.1	1.4	18.1	12.1	8.9	0.9	0.6	5.4	5.1
Fineness modulus	2.87			2.71			4.08		3.54	
Voids content (%)	-			-			41	39	43	44
Loose bulk density (kg/m <sup>3</sup> )	-			-			1450	1479	1207	1171
Dry-rodded density (kg/m <sup>3</sup> )	-			-			1543	1586	1300	1293
Attached mortar volume (%)	-			-			-	-	51	52

Note: SSD = Saturated surface-dry

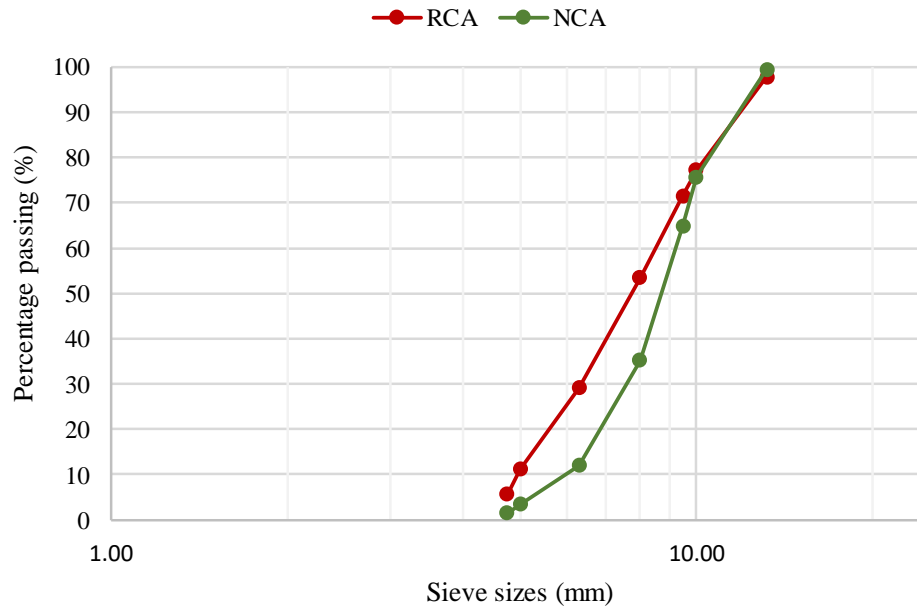


The average absorptions of NFA and RFA are 1% and 13% respectively. While the absorption of the former increases with the particles size, that of the latter decreases as the particles size increases. This property of RFA highlights the reason why its usage for concrete production is limited. The average absorptions of NCA and RCA are individually 0.8% and 5.3%. Both the loose bulk and dry-rodded density of fine and coarse RA are found lower than those of their comparable NA, while the voids content of RA is higher than that of the NA.

Three types of steel fibre that differ only in shape, as shown in Fig. 3, were investigated in this research. They have similar properties as described in Tables 3 & 4.



**Fig. 1.** Particles size distribution of fine aggregates.



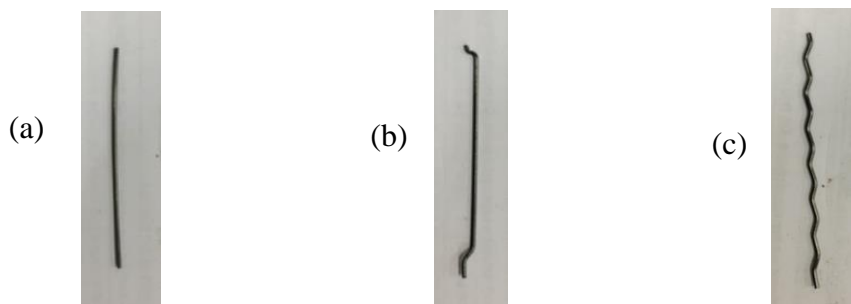
**Fig. 2.** Particles size distribution of coarse aggregates.

**Table 3.** Properties of steel fibres.

Steel fibre types	Length (mm)	Diameter (mm)	Aspect ratio	Cross section	Tensile strength (MPa)
Straight					
Hooked-ended	60	1.0	60	Circular	1900
Undulated					

**Table 4.** Composition of steel fibres.

Material	Chemical composition (%)								
	C	Si	Mn	P	S	Cr	Ni	Cu	Fe
Carbon steel	0.7	0.22	0.55	0.015	0.006	0.02	0.01	0.03	Balance



**Fig. 3.** 60mm steel fibres: (a) Straight (b) Hooked ended (c) Undulated

### 3.2 *Composition and production of concrete*

The experimental campaign was divided into two phases and concrete in each phase was designed to meet a target strength of 40MPa. The objective in phase I was to optimize SF volume fractions using both conventional and the EMV mix design methods. For this purpose, a total of 8 concrete mixes were formulated as shown in Table 5. In the conventional method, the RAC mix consisted of 100% RA and was designed according to the British Department of Environment (DoE) approach [44]. Five different SF volume ratios (0.125%, 0.25%, 0.5%, 1.0% and 1.50%) were integrated in the mix, in turn, and the cube specimens produced were subjected to compression testing after 7 days of curing by water immersion. At this stage, having ascertained the mix with optimum SF content (see Section 4.1), the same mix was duplicated to investigate the performance of each of the three SF used in this study. Similarly, three mixes composed of three SF volume fractions (0.25%, 0.50% and 0.75%) were prepared using the EMV mix proportioning method. These mixes consist of 60% RA and 40% NA by volume for both fine and coarse aggregates, and the resulting concretes were tested in compression after 7 days of curing.

With the optimum SF volume ratio known, 3 mixes were designed in phase II as given in Table 6, to investigate the effects of mix design method on the properties of RAC incorporating SF. In a related investigation by the authors [25], it was found that the American Concrete Institute (ACI) method [45] is preferred to the corresponding DoE approach, for the preparation of RAC mix. Hence, the ACI mix design approach was adopted in this phase. It should be noted however, that the preference was based mainly on the utilization of a lesser amount of cement by the ACI method compared to the DoE approach. So, natural concrete (NC) (referred to as the ‘reference mix’) and steel fibre-reinforced recycled aggregate concrete (SFRRAC) were designed according to the ACI guide. Whereas the former constitutes entirely of NA, the latter

is made up of 100% RA plus 1% SF content obtained in the first phase of the experiment. The third mix was designed with the EMV technique, comprising of both NA and RA with the addition of 0.5% SF content and labelled steel fibre-reinforced blended aggregate concrete (SFRBAC).

For all mixes (both in phase I & II), NA were used in their oven-dry form while the RA were used in the moisture condition as received from the supplier. The fine aggregates content in each mix, according to the three size fractions stated in Section 3.1, is 50%, 33.3% and 16.7% respectively, while that of the coarse aggregates is 70% and 30%, respectively. These ratios were found appropriate for the desired consistency (finishing) of fresh concrete and similar particles size gradation between NA and RA. Water-to-cement ratio of 0.42 was kept constant (see Table 6) for all mixes in stage two, irrespective of the design mechanism used.

A series of trial mixes were conducted at both stages of the experiments. This was to establish the amount of superplasticizer needed for each mix, in order to achieve comparable workability, as the presence of both RA and SF reduces the flowability of concrete. The trial mixes also helped to determine the combination of coarse aggregates that gave concrete of desirable homogeneity and surface finishing when poured into the moulds. Mixing of concrete constituents was done in a mechanical mixer, in the manner described in Tam and Tam [38]. The fresh concrete was compacted in the relevant moulds in different layers using a vibrating table. The type of concrete mix as well as the shape of specimens influenced the number of layers required to attain full compaction. Cube specimens of NC were compacted in 2 layers while those of SFRRAC and SFRBAC were done in 3 layers. For the cylinders, **NC** and the SFRC were compacted in 3 and 5 layers respectively. Both the SFRC and the NC were compacted in a single layer for the prisms.

**Table 5.** Phase I – Concrete mixes and the results of the optimization of steel fibres using both normal and the EMV methods.

Mix ID	Design method	Mix Proportions (kg/m <sup>3</sup> )								w/c	Slump (mm)	ACS <sup>§</sup> (N/mm <sup>2</sup> )
		Water	Cement	NCA	RCA	NFA	RFA	SP <sup>β</sup>	SF <sup>μ</sup> (%)			
Mix 1	DoE	205	525	0	750	0	890	3.70	0.125	0.39	155	39.3
Mix 2	DoE	205	525	0	750	0	890	3.70	0.250	0.39	165	40.8
Mix 3	DoE	215	550	0	750	0	890	3.85	0.500	0.39	155	40.4
Mix 4	DoE	225	575	0	750	0	890	4.03	1.000	0.39	120	44.0
Mix 5	DoE	225	575	0	750	0	890	4.03	1.500	0.39	65	45.8
Mix 6	EMV	153	364	493	754	203	305	2.50	0.250	0.42	150	39.9
Mix 7	EMV	153	364	493	754	203	305	3.00	0.500	0.42	165	47.9
Mix 8	EMV	153	364	493	754	203	305	3.20	0.750	0.42	170	44.6

Note: w/c = water-to-cement ratio.

<sup>β</sup>Superplasticizers added as percentage of cement content.

<sup>μ</sup>Steel fibres added as percentage of concrete volume.

<sup>§</sup>Average compressive strength for 6 cubes.

**Table 6.** Phase II – Dry-weight composition of concrete mixes.

Concrete Mix	Design method	Mix Proportions (kg/m <sup>3</sup> )								w/c
		Water	Cement	NCA	RCA	NFA	RFA	SP <sup>β</sup>	SF	
NC	ACI	213	507	856	0	707	0	1.27	0.00	0.42
SFRRAC	ACI	213	507	0	754	0	534	3.80	78.50	0.42
SFRBAC	EMV	153	364	493	754	203	305	12.00	39.25	0.42

Note: w/c = water-to-cement ratio.

<sup>β</sup>Superplasticizers added as some percentage of cement content.

### 3.2.1 Overview of the EMV method

The EMV technique utilizes the attached mortar present in the RCA in its design approach.

The real attached mortar volume (AMV) of the RCA is used to determine the substitution level of NCA, by comparing its value with the theoretical AMV calculated from Equation (3). In this method, the attached mortar is treated as a proportion of the total mortar in RAC. This implies that the overall mortar volume of RAC is a combination of the old (attached mortar) and new

pastes. Therefore, the EMV approach ensures that the preparation of the RAC mix is carried out to have total paste akin to that of NAC mix made of virgin natural aggregates. The sequence of this method, including an additional step for the incorporation of RFA (applied in the current study), has been discussed in detail in a similar study [25]. There is a feasibility of 100% replacement if, and only if, the theoretical AMV is greater than the real value obtained using the procedure described in the work of Abbas *et al.* [46]. The maximum AMV is obtained from the expression:

$$AMV_{max} \% = \left( 1 - V_{DR-NCA}^{NAC} \times \frac{SG^{NCA}}{SG^{RCA}} \right) \times 100 \quad (3)$$

$V_{DR-NCA}^{NAC}$  represents the dry-rodded volume of the NCA in NAC,  $SG^{NCA}$  is the specific gravity of NCA and  $SG^{RCA}$  is the specific gravity of RCA.

### 3.3 Tests

The mechanical properties of hardened concrete and workability of fresh concrete were investigated according to the relevant standards presented in Table 7. The determination of aggregates properties given in Table 2 was carried out in line with the following guidelines:

- Sieve analysis of fine and coarse aggregates: ASTM C136 – 14 [47]
- Bulk density and voids in aggregates: ASTM C29/C29M – 17a [48]
- Specific gravity and absorption of fine aggregate: ASTM C128 – 15 [49]
- Specific gravity and absorption of coarse aggregate: ASTM C127 – 15 [50]
- Residual mortar content of the RCA: Abbas et al. [46]

**Table 7.** Test information for fresh and hardened concrete.

Phase	Property	Specification	Specimens		
			Size and shape	Duplicates*	Age (days)
I	Workability	BS EN 12350 – 2 [51]	–	–	–
	Compressive strength	BS EN 12390 – 3 [52]	100mm Cubes	6	7
II	Workability	BS EN 12350 – 2 [51]	–	–	–
	Density	BS EN 12390 – 7 [53]	100mm Cubes	5	28
	Compressive strength	BS EN 12390 – 3 [52]	100mm Cubes	15	7, 28, 56
	Tensile strength	BS EN 12390 – 6 [54]	150 × 300mm Cylinders	3	28
	Flexural strength	ASTM (C78[55]; C1609 [56])	150 × 150 × 500mm Prisms	2	28
	Water absorption	BS 1881 – 122 [57]	100 × 200mm Cylinders	3	28

*\*Number of specimens for each mix*

## 4. Results and discussion

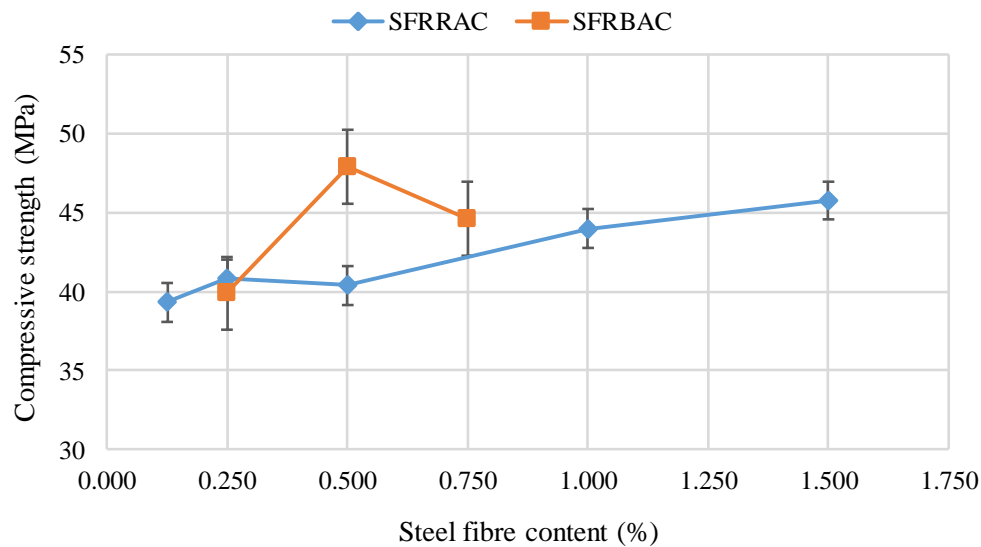
### 4.1 Optimization of steel fibres – Phase I

The mix proportions for the optimization process of SFRRAC and SFRBAC are given in Table 5 while Fig. 4 shows the compressive strength responses for each SF volume ratio considered. It can be observed that, SF either increases or decreases the compressive strength of concrete, depending on volume fraction of the SF used. In the present study, 1% SF content was chosen as the candidate for SFRRAC on the basis of strength, cost and workability (measured in terms of slump value). This is similar to the volume fraction used in an investigation carried out with double hooked-ended SF of aspect ratio of 65, using the conventional mix design method [19]. For the SFRBAC, 0.5% SF content offered the best result of the three volume ratios considered. It can therefore be deduced that mix design method for SFRC affects the optimum SF volume ratio since certain SF content causes a reduction effect on the compressive strength of the concrete as well as workability of the fresh concrete. In addition, Table 8 shows that the mix with the undulated SF gave the highest strength and was therefore selected for the phase II of the experiment.

**Table 8.** Results of the test on steel fibre types.

Steel fibre type	Compressive strength (N/mm <sup>2</sup> )	Std	Slump (mm)
Straight	42.0	1.64	117
Undulated	45.2	1.81	125
Hooked-ended	43.7	1.20	120

*Std = standard deviation*

**Fig. 4.** Optimization of steel fibre for SFRRAC and SFRBAC mixes.

#### 4.2 Fresh properties of concrete – Phase I & II

The workability of the concrete mixes was measured in terms of slump value. The inclusion of RA and SF as well as mix design method affect the workability of concrete. The fragments of the dry mortar present in RA increases the water demand for recycled concrete. It can be observed from Table 5 that the addition of SF requires more superplasticizer to maintain similar slump values with the other mixes. This statement is in agreement with the findings of previous researchers [19–21]. Also, despite using lesser optimum SF content, the use of EMV mix proportioning method induced up to 68% additional superplasticizer in relation to its parallel ACI method. This can be traced to a higher aggregate content and lesser amount of water in the mix developed with the EMV guidelines.



### 4.3 *Mechanical properties of concrete – Phase II*

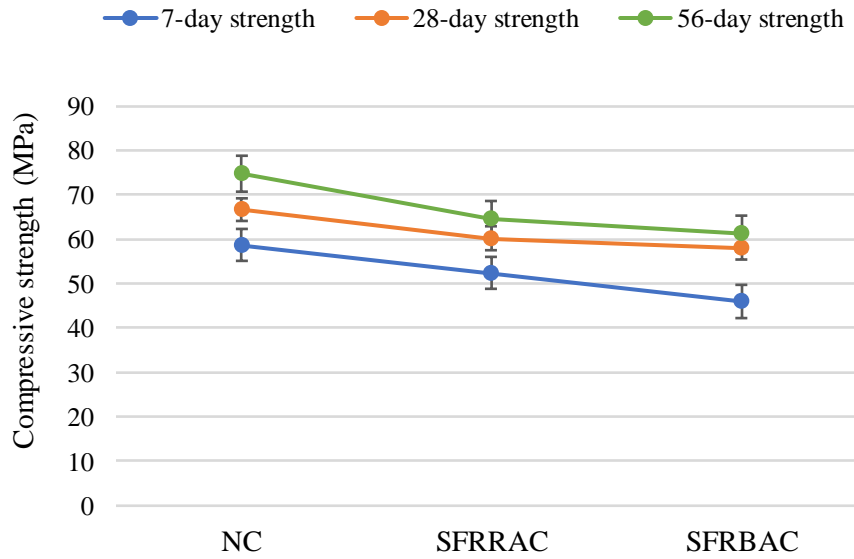
#### 4.3.1 *Hardened density*

The average density of 15 specimens tested for each mix showed that the NC has a greater density when compared with the SFRRAC and SFRBAC. The NC, SFRRAC and SFRBAC showed density values of  $2370\text{kg/m}^3$ ,  $2230\text{kg/m}^3$  and  $2350\text{kg/m}^3$ , respectively. This result shows that the density of RAC is still lower than that of the conventional concrete irrespective of the addition of SF. This is because of the porosity and lightweight nature of the dry mortar adhering to the RA.

#### 4.3.2 *Compressive strength*

In phase I of the experiments, the results show that the compressive strength of concrete is affected by the quantity of SF. On one hand, there is an enhancement in strength of recycled concrete containing SF, if the appropriate volume fraction of the SF is used. The mix design method adopted also contributes to this trend. On the other hand, addition of high volume of SF causes “balling effect” in concrete leading to a reduction in strength.

The compressive strength obtained for all mixes at different ages in phase II is presented in Fig. 5. As expected, there is a strength development with age, notwithstanding the mix design approach and type of aggregate used. Although the target strength was achieved by all the mixes, both RA and mix proportioning method impacted on the compressive strength of SFRRAC and SFRBAC when compared with NC. This is due to two interfacial transition zones present in the recycled concrete, one formed by the residual mortar and the other by the fresh mortar [58], resulting to a lower strength paste relative to a normal concrete. The SFRRAC designed with the orthodox method showed approximately 12% more strength at 7 days than its companion SFRBAC designed with the EMV method. This variation, however, was reduced to only 4% at 28 days and it should be recalled (from Table 6) that the EMV technique used about 30% lesser cement content than the conventional method.

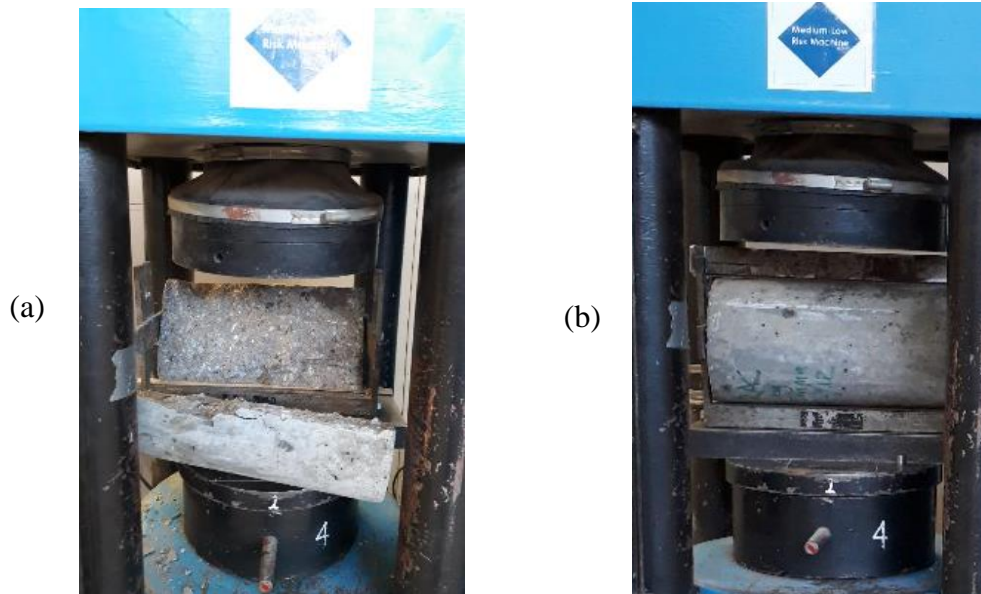


**Fig. 5.** Compressive strength of concretes tested at different ages.

#### 4.3.3 Tensile splitting strength

The tensile splitting strength of all the mix studied are presented in Table 9. It can be observed that the presence of SF in RAC greatly improved this property. Also, concretes containing RA had higher tensile splitting strength than the conventional concrete prepared with NA. Nevertheless, SFRRAC and SFRBAC showed 38% and 10% higher strength relative to the NC, respectively. This is mainly as a result of the inclusion of SF, which bridges cracking propagation thereby improving post-cracking resistance and toughness of the concrete [24]. Even with up to 30% lower cement content in the case of SFRBAC compare to NC, the SFRBAC still gave a higher value of tensile strength. An underlying factor is the higher amount of superplasticizer as reported by Soares et al. [34] who noted about 39% improvement in tensile strength when superplasticizer was added to concrete mix. In terms of mix design approach, Table 9 reveals that this concrete property is affected. A significant difference of approximately 32% exists between SFRRAC and SFRBAC, in favour of the former. Obviously, from Table 6, the quantity of SF involved in SFRRAC mix is doubled that in SFRBAC mix. Thus, the observed result is expected. However, the SFRC failed with almost

no visible cracks while their parallel unreinforced NC failed catastrophically, splitting into two as shown in Fig. 6.



**Fig. 6.** Tensile failure mode: (a) NC (b) SFRC

#### 4.3.4 Flexural strength

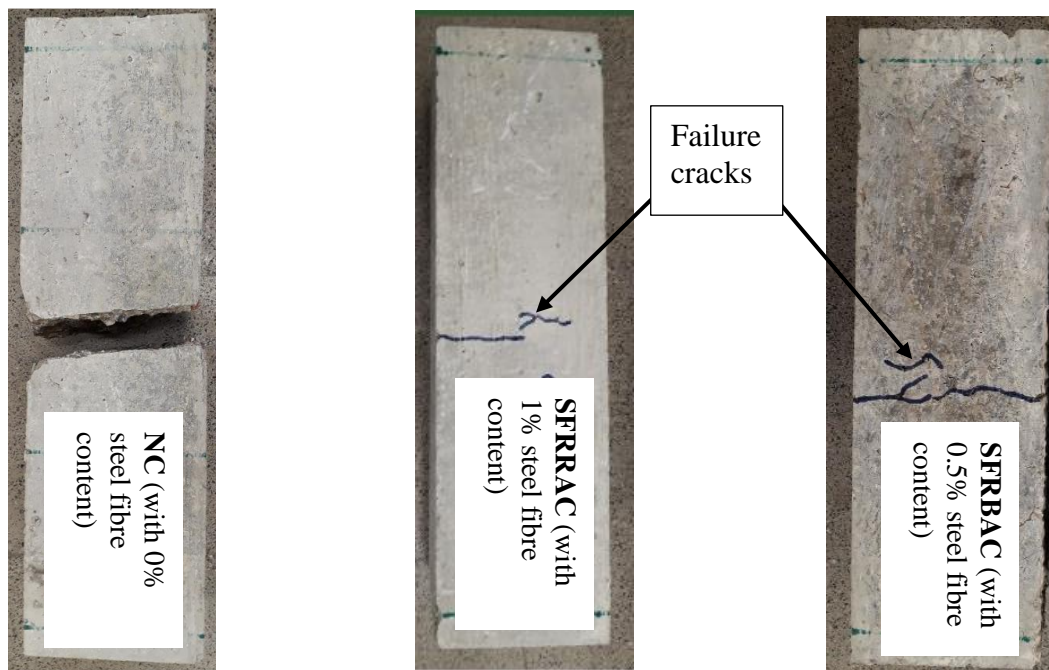
According to the results presented in Table 9, both SF and mix design method influenced the flexural strength of the concrete. The presence of SF in SFRRAC designed with the conventional method resulted in about 4% improvement in the flexural strength relative to the reference mix prepared with NA. On the other hand, unlike the tensile splitting strength, the use of EMV mix design for the steel fibre-reinforced concrete (i.e. SFRBAC) reduced flexural strength by up to 17% in comparison with the NC. Comparing SFRRAC and SFRBAC, a difference of approximately 20% in flexural strength is recorded in favour of SFRRAC. This can be attributed to greater amount of optimum SF content engendered by the use of the traditional method. However, in terms of failure mode, the NC specimens failed in a brittle manner while the SFRC (regardless of the mix design method) exhibited a ductile failure mode as shown in Fig. 7. The ductility is stimulated by the presence of SF in the latter [59]. The crack patterns developed by SFRRAC and SFRBAC as in Fig. 7 reveal that SFRRAC has a higher

resistance. This is because its mix contains more SF (that is 1% by volume of concrete) than that of SFRBAC (which is 0.5% by volume of concrete). The load versus displacement diagram of the fibre-reinforced concretes in Fig. 8 shows that the specimens reached their ultimate load without sudden failure, unlike the NC specimens (with no SF) which failed at the instance of the maximum load. It can also be seen that a higher SF volume fraction results in a greater peak load. This is consistent with the results published by Gao et al. [21].

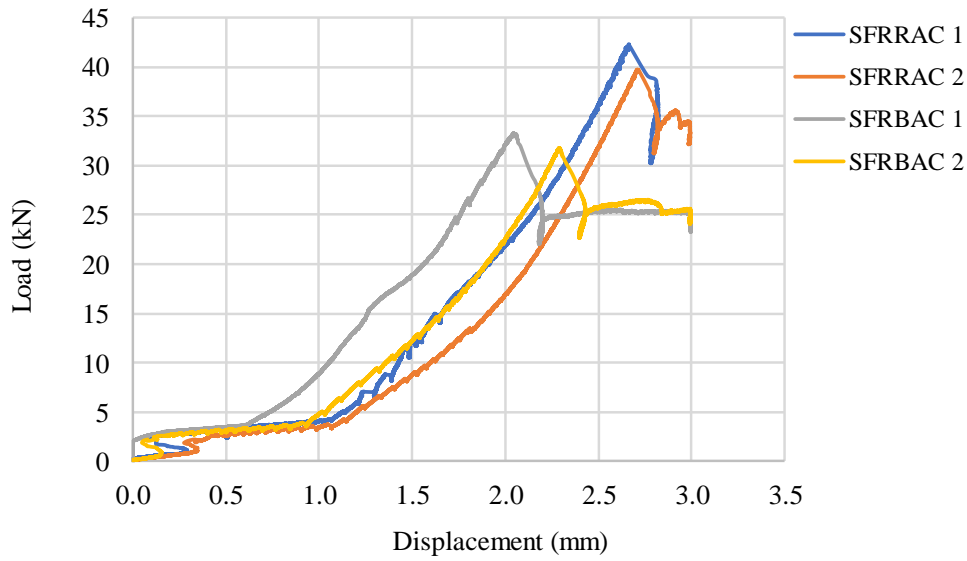
**Table 9.** Results of the test on hardened concrete.

Concrete Mix	Splitting tensile strength (MPa)	Flexural strength		Water absorption	
		(MPa)	Std	(%)	Std
NC	3.80	5.04	2.71	3.1	0.00
SFRRAC	6.15	5.27	1.06	6.1	0.13
SFRBAC	4.20	4.20	1.07	3.4	0.15

*Std = standard deviation*



**Fig. 7.** Flexural failure mode: NC, SFRRAC and SFRBAC respectively.

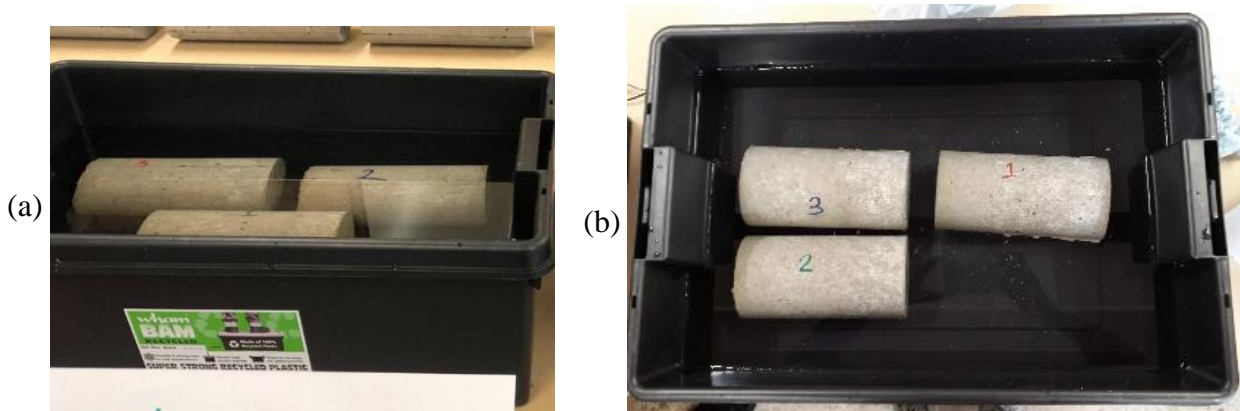


**Fig. 8.** Load-displacement plot of steel fibre-reinforced recycled concretes prepared by the conventional and the EMV methods.

#### 4.3.5 Water absorption

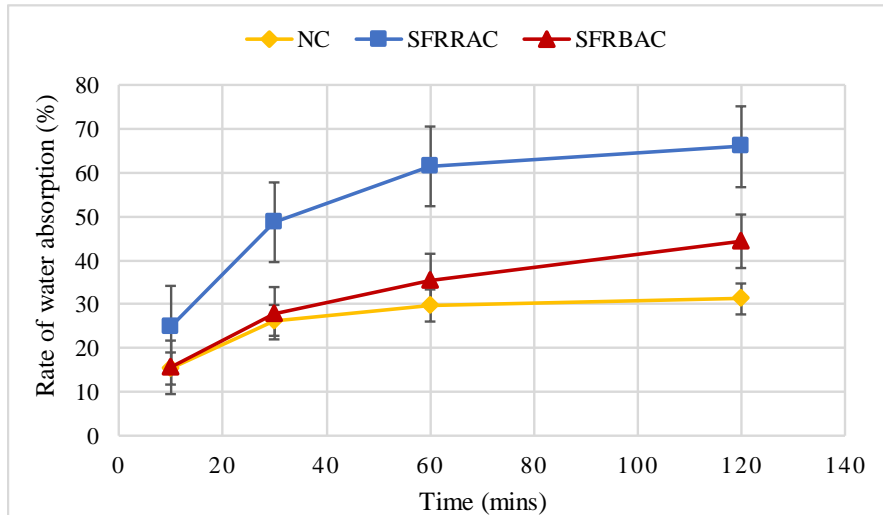
Water absorption capacity by immersion was studied after 28 days of curing the concrete specimens (see Fig. 9). The results presented in Table 9 show that the absorption of RAC incorporating SF is affected by the mix design method and suggest that this durability property of concrete is improved with the EMV technique. In comparison with the NC, the SFRRAC and SFRBAC had higher absorptions in excess of 49% and 8.8% respectively. This is expected since SFRRAC is made of 100% replacement ratio with both fine and coarse RA as opposed to 60% substitutions for the SFRBAC. Also, the inclusion of SF increases pore density [60], hence the SFRRAC with an optimum SF volume ratio of 1% had higher porosity than does SFRBAC with an optimum SF content of 0.5%, thus a higher water absorption. Soares et al. [34] explained that water absorption is dependent on pore structure of aggregate and the amount of water contained in the concrete itself. However, in this research, the same quantity of water

was used for both NC and SFRRAC mixes as shown in Table 6. Therefore, it can be concluded that the high-water absorption of RAC is mainly as a result of the porosity of the RA.



**Fig. 9.** Set-up for water absorption capacity test by immersion; (a) Side view (b) Top view.

The Fig. 10 shows the rate of water absorption of the concretes observed under some cumulative immersion periods, up to 120 minutes. Obviously, from the slopes of the plots, it can be deduced that the rate of absorption decreases with time. Although the SFRRAC specimens have a higher water absorption relative to those of SFRBAC, they have an identical rate of absorption. This is evident in their gradients and can be attributed to the same amount of RCA in both mixes.



**Fig. 10.** Rate of water absorption of concrete mixes at 28 days.

## 5. Conclusions

Investigations into the effect of conventional and the Equivalent mortar volume (EMV) mix design methods on recycled aggregate concrete (RAC) mixes incorporating steel fibre (SF) is presented and analysed in this paper. The following conclusions are drawn from the study:

- Out of the three types (in terms of shape – straight, hooked ended and undulated) of SF investigated, the undulated type gave the best performance in terms of compressive strength of the concrete.
- Different volume fractions of SF considered show that the effect of SF on the compressive strength of concrete remains a function of the amount used, and this suggests the need for the optimization of SF prior to adoption in concrete manufacture. It must also be stated that the optimum content varies with respect to mix design method. In this research, while the conventional method gave an optimum SF content of 1% by volume of concrete, the EMV gave 0.5%.
- The results of this study show that the EMV mix proportioning method is beneficial and can be applied to the production of steel fibre-reinforced concrete. However, it is

worth noting that this method requires over 68% amount of superplasticizer than its comparable conventional method, to attain similar workability.

- From cost point of view, the EMV method is preferable to the conventional method following the lower optimum SF volume ratio and the gain of 30% cement content achieved by the use of the EMV technique. Nevertheless, the conventional method offers concretes of better properties (except for water absorption capacity) than its equivalent EMV approach.
- The contribution of SF to the mechanical properties of concrete is highest in the tensile splitting strength and, irrespective of the mix design method used, the tensile splitting strength of steel fibre-reinforced recycled concretes is higher than that of the normal concrete. This is attributed to the ability of SF to restrict cracking propagation, thus sustaining more load.
- Although the rate of water absorption of the recycled concretes produced using either methods appears the same, the actual absorption of steel fibre-reinforced recycled aggregate concrete manufactured by the conventional approach, is 44% higher than that of steel fibre-reinforced blended aggregate concrete prepared with the EMV approach because of the higher amount of recycled aggregates in the former. Overall, the presence of recycled aggregates and SF raised the water absorption capacity of the resulting concretes by up to 49% above their comparable normal concrete produced with natural aggregates.

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